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## NEP Systems Engineering Efforts in FY92—Plans and Status

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## NEP SYSTEMS ENGINEERING EFFORTS IN FY92 PLANS AND STATUS

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### INTRODUCTION

A systems engineering effort has been initiated by NASA in FY92 to define, address, and resolve issues associated with the use of Nuclear Electric Propulsion (NEP) for megawatt (MW) space propulsion applications associated with the Space Exploration Initiative (SEI). It is intended that key technical issues will be addressed by activities conducted in the early years of a project in NEP, with the objective of resolving such issues. Also, in response to more recent programmatic direction, a concept definition activity for 100 kilowatt NEP is being initiated. This paper will present key issues associated with megawatt NEP, and the plans and status for their resolution, and present the scope and rationale for the 100 kilowatt concept definition activity.

### BACKGROUND

Responding to user needs for advanced propulsion systems for science and exploration, NASA's Office of Aeronautics and Space Technology (OAST) has established a Transportation Technology Thrust within its Integrated Technology Plan (ITP).<sup>1</sup> As stated in the ITP: "The space research and technology focused program goal for nuclear electric propulsion (NEP) addresses three major applications: (a) robotic deep space exploration (e.g., to the outer planets); (b) unpiloted cargo vehicles (in support of a human mission to Mars); and (c) piloted Mars transfer vehicles."<sup>2</sup>

In concert with this program backdrop, a technology project has been initiated by NASA Lewis Research Center's Nuclear Propulsion Office (NPO) which has a work breakdown structure (WBS) with the following six major elements: Concept Development/Systems Engineering, Project Management, NEP Technology, Innovative Technology, NEP Facilities, and Safety/Quality Assurance/Reliability/Environment.<sup>3,4</sup> This paper will discuss activities taking place in FY92 which fall under the first and last elements in this list, namely the Concept Development/Systems Engineering and the Safety/ Quality Assurance/Reliability/Environment elements.

### MW NEP KEY TECHNICAL ISSUES

Key technical issues are being addressed: system performance, flight system processing (on-orbit deployment), and operational reliability. Each of the following sections describes activities that have begun in FY92 to address these issues.

## System Performance

Greater depth is required of system definitions for megawatt NEP, to maintain justification of performance claims and assess the impact of technology developments. NEP subsystem modeling for reactors, power conversion, power management and distribution, heat rejection, and electric thrusters must be provided to a finer degree than has been provided to date. Algorithms to describe the physical phenomena associated with primary and secondary heat transport, turbine efficiency, removal of inconvertible heat, the conditioning and transmission of electricity, to name a few areas, are required. Overall performance will primarily be measured in terms of mass and efficiency.

Not only is greater depth needed in MW NEP system definitions, but also the capability to perform end-to-end system optimization. System optimization is the process of determining the most desirable system operating conditions, based on a simultaneous solution of subsystem governing equations for overall system minimum mass and maximum efficiency. System optimization is a process enabled by analytical modeling.

NASA LeRC has initiated a technical effort to develop software tools to achieve greater depth to system definitions and to enable end-to-end optimization of megawatt NEP systems. The technical approach assumes the development of separate software submodules to model the major subsystems inherent to MW NEP. As shown in Figure 1, submodules to be included are for reactor, shielding, primary heat transport, power conversion, heat rejection, power management and distribution (PMAD), structure, and thruster, with overall control maintained by a master program module.

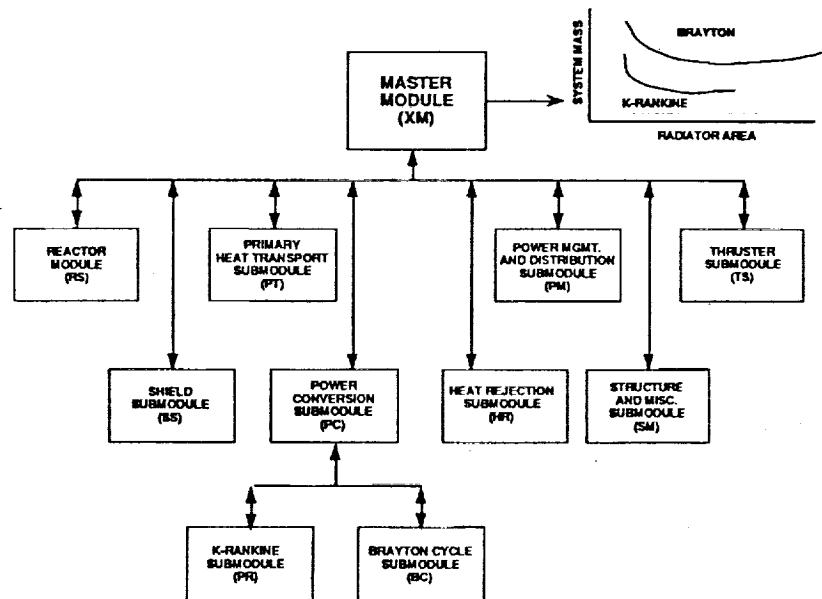


Fig.1. Nuclear electric propulsion system optimization code: Variable Prefix Diagram ( ).

### Reactor and Shielding

Reactor and shielding subsystems will be characterized for power levels and lifetimes needed for SEI missions. Requirements for the reactor subsystem are: 2 - 10 year lifetime, 10 - 50 MWt, for operating environments from low Earth orbit to interplanetary space; requirements for shielding are: 5 rem/year at 100 meters for crew (instrument rating for cargo), using shadow angles large enough to cover all attached vehicle structure.

Reactor concepts to be modeled are Uranium-Nitride-fueled pin-type (UN/

Fuel Pin), Uranium Tungsten-Rhenium Cermet (U/W-Re Cermet), and Uranium Carbide with Graphite (or composite) matrix (UC/C matrix). Coolant temperatures to be considered are 1,100 - 1,600°K for the UN/Fuel Pin and U/W-Re Cermet concepts (lithium cooled) and 1,600 - 2,200°K for the UC/C matrix concept (Helium, or Helium-Xenon cooled). The effects of material strength, temperature, working fluid/materials compatibility, burn-up, swelling, fission gas release and retention, and reactor control will be considered for a range of power levels, operating temperatures, and lifetimes. Shield sizing and behavior with respect to dose, distance, lifetime, reactor type, power level will be modeled with shield mass, volume, materials, and cooling requirements (if needed) calculated or identified.

#### Power Conversion, Heat Rejection, and PMAD

Power conversion, heat rejection, and power management and distribution (PMAD) subsystems are being modeled and characterized at power levels needed for SEI mission needs. Requirements for these subsystems are: 2 - 10 year lifetime, 100 - 10,000 kWe, for operating environments from low Earth orbit to interplanetary space.

Power conversion technologies being modeled are Potassium (K) Rankine cycle and Brayton cycle dynamic conversion options. Characteristics to be modeled include subsystem mass, efficiency, and dimensions as a function of input parameters such as: turbine design (axial or radial), turbine inlet temperature, inlet/outlet turbine temperature ratio, power level (synonymous with working fluid flow rate), lifetime, materials, and redundancy. K-Rankine subsystems will be modeled for turbine inlet temperatures from 1,100 - 1,600°K at turbine inlet/outlet temperature ratios from 1.25 - 1.6, while Brayton subsystems will be modeled for turbine inlet temperatures from 1,100 - 1,600°K at turbine inlet/outlet temperature ratios of 2.5 - 4.0.

Rankine cycle heat engines produce useful work by heating a fluid to become a gas, employing the heated gas to do useful work, and condensing the gas back into liquid state. Under this modeling effort, the Rankine cycle power conversion option assumes that a primary lithium loop supplies heat from the reactor to the boiler and reheater. This is the basis for the schematic shown in Figure 2 which also depicts the other components comprising

this power conversion system. Boiler and reheater will be modeled as a once through design with lithium on the shell side and potassium on the tube side.

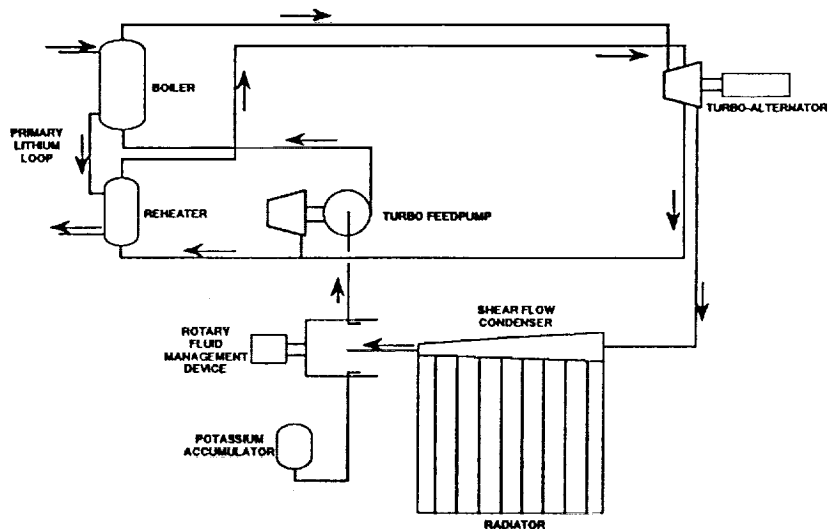


Fig 2. Potassium-rankine power conversion system schematic.

Turbo-alternator will be modeled as a multistage axial reaction turbine with a two-pole toothless (permanent magnet) alternator. Condenser will be modeled as a shear-controlled flow condenser co-serving as a manifold for a heat pipe radiator. Turbopump will be modeled as a single stage centrifugal impeller with inducer, driven by a 45% efficient partial admission turbine. Head losses and piping sizes will be computed also.

Brayton cycle heat engines are single phase working fluid engines which produce useful work by heating a gas under a relatively constant pressure process, employing the heated gas to do useful work, and cooling the gas under another relatively constant pressure process to get it back into its original preheated state. This is the basis for the schematic shown in Figure 3 which also depicts the components comprising this power conversion system. Under this modeling effort, the Brayton cycle power conversion option will have the capability to model the heat input to the gas as either by direct heating (gas

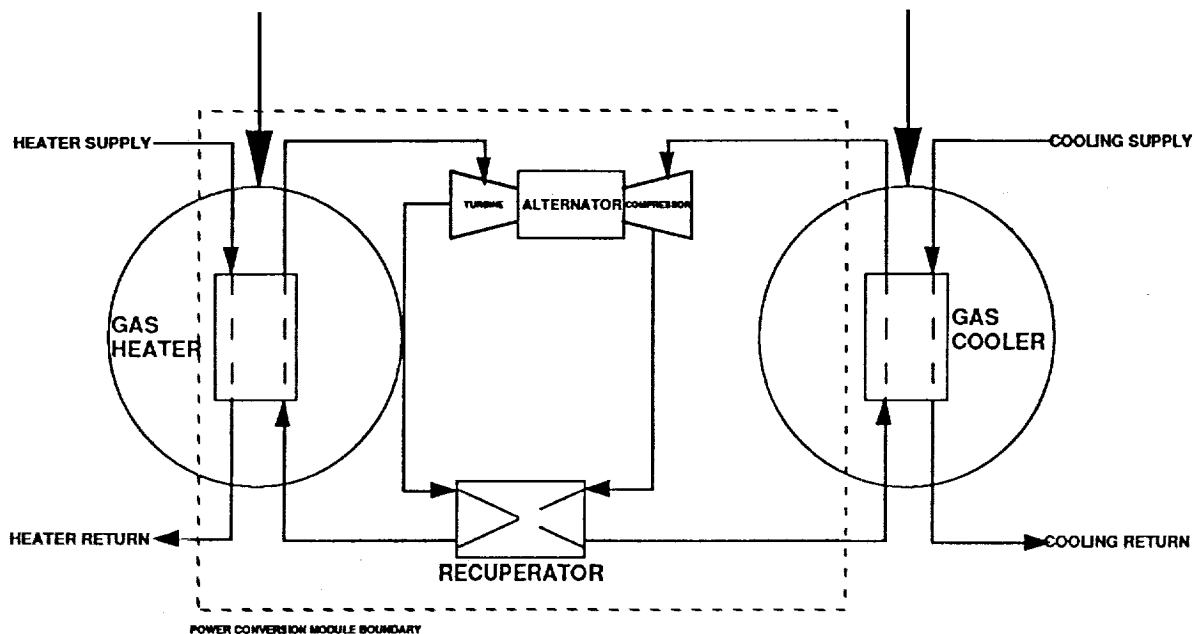


Fig.3. Brayton power conversion system schematic.

circulated through a reactor) or by indirect heating (gas flowing through a liquid-to-gas heat exchanger). The same heat exchanger model will be employed in both gas heater and gas cooler submodels, which has assumed tube and shell configuration with liquid on the tube side. In addition, the gas cooler submodel will include the capability for direct gas cooling via a gas-to-heat-pipe heat exchanger. Turbo-alternator-compressor will have the capability to be modeled as either an axial or radial machine with a two-pole toothless (permanent magnet) alternator. A ducting algorithm will compute ducting diameter, length, and mass, multifoil insulation mass, and total mass for each ducting segment as well as provide gas Reynolds number and pressure drop.

Heat rejection subsystem modeling will be established upon heat pipe based radiator concepts. Radiator subsystem specific mass (mass per unit area) determines overall power system optimal temperature and mass character-

istics, as well as vehicle size (length and area). Characteristics to be modeled include radiator area, length, and width, heat pipe dimensions, and manifold/heat exchanger, ducting, and pump dimensions and mass as functions of inlet temperature, working fluid, radiator geometry, and material. Heat rejection requirements are from 100 to 50,000 kWt, at temperatures ranging from 750 - 1,250°K (K-Rankine) and 300 - 1,000°K (Brayton) and operating environments from low Earth orbit (LEO) to interplanetary space.

The analysis methodology for a heat pipe based algorithm to support the heat rejection requirements of both a Rankine cycle heat engine (shear flow condenser) and Brayton cycle heat engine (direct gas cooling or liquid loop cooling) is shown in Figure 4. Liquid loop cooling will use lithium or a sodium-potassium (NaK) fluid mixture. Heat pipe radiator modeling will encompass a number of heat pipe structural materials (refractory metal alloy, carbon-carbon composite, and ceramic fabric), and will include heat pipe

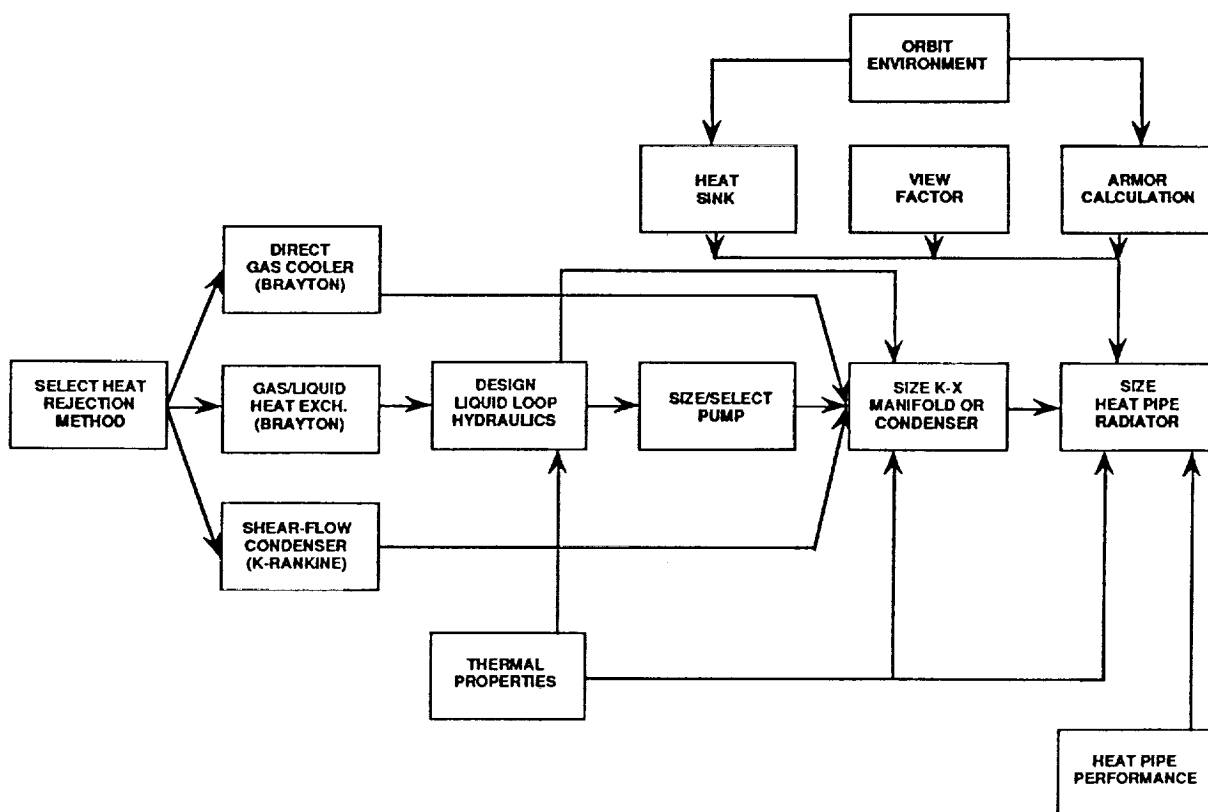


Fig.4. Analysis methodology for heat rejection subsystem

redundancy requirements (reliability based calculation), radiator performance predictions for various heat sink temperatures (i.e., LEO, interplanetary space, and 0.5 astronomical unit), armoring requirements, and provide heat rejection performance for various radiator geometries. Heat pipe performance is based upon an internal model which has considered wick structures, arteries, porosity, and wetting angle.

Power management and distribution (PMAD) subsystem modeling will consider electrical power conditioning, transmission, and processing between

point of generation (alternator) to point of use (thruster). Characteristics to be modeled include component and subsystem mass, size, and efficiency as functions of power level, transmission line length, engine voltage, alternator frequency, and electronic coldplate temperature. PMAD requirements include electrical power from 100 to 10,000 kWe, voltages from 200 to 10,000 volts, AC frequencies from 400 to 20,000 Hz, and electronic coldplate temperatures from 300 to 500°K under operating environments from low Earth orbit (LEO) to interplanetary space.

The reference architecture is a low frequency design (using a Litz wire transmission cable) that is based directly on the operating frequency and voltage output of a 3-phase alternator. A schematic showing alternator, transmission line, load switchgear, power processor, and thrusters for a 5 MWe power distribution subsystem appears in Figure 5 but the depiction is not meant to imply that the number of thrusters per subsystem has been optimized.

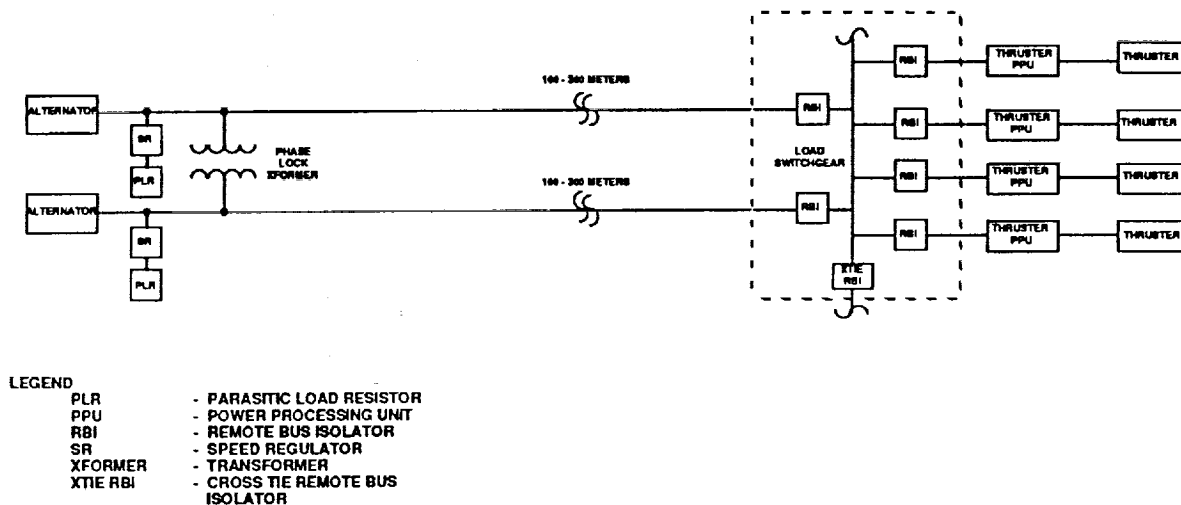


Fig.5. Low frequency PMAD architecture for 5 MWe power/propulsion module

Based on available transmission line models to date, the low frequency PMAD architecture has the lowest mass, highest efficiency, and the least complexity. The PMAD architecture incorporates both ion and magnetoplasmadynamic (MPD) thruster power processing units (PPUs), with the capability to model ion thruster PPU both with and without a beam power supply transformer. Both a single or a counter rotating alternator option is available.

#### Thruster

Thruster subsystems will be modeled and characterized for power levels and lifetimes needed for SEI mission needs. Requirements for the thruster subsystem are: subsystem burn times from 1 - 8 years (supports a 2 - 10 year system lifetime), 100 - 10,000 kWe total power input, 4,000 - 10,000 seconds specific impulse, and operating environments from low Earth orbit to interplanetary space.

Thruster concepts to be modeled are the ion engine (electrostatic) and electromagnetic (MPD) options. Characteristics to be modeled include subsystem mass, efficiency, and dimensions as a function of input parameters such



as: specific impulse, electric power to be processed, propellant type, lifetime, and redundancy.

### **NEP Flight System Processing**

The installation in low Earth orbit of a megawatt NEP space vehicle, comprised of a sizeable waste heat rejection subsystem, may place demanding requirements on Earth-to-orbit (ETO) and on-orbit-assembly (OOA) infrastructures. Consideration of how a heat rejection subsystem comprised primarily of heat pipes will be packaged within the volumetric constraints of an existing or planned ETO system is critical. Likewise, the volume characteristics of this required heat rejection subsystem as well as the lengthy NEP space vehicle central structure must be assessed for their impact on the on-orbit assembly of the vehicle. Deployable trusses and joinable subsystem modules will be necessary for the on-orbit emplacement of a megawatt NEP space vehicle.

To address flight system processing issues such as ETO and OOA, NASA has defined a study task in NEP flight system processing, operations, and disposal for a piloted NEP vehicle. As a part of this task, launch packaging and on-orbit deployment approaches for a megawatt NEP vehicle will be proposed, and their impact on NEP system definition determined. Also, heavy lift launch (ETO) vehicle requirements will be determined, including number of launches and launch sequence of elements to support OOA. The task will also consider NEP spiral operations and crew rendezvous, multi-mission vehicle refurbishment and maintenance in LEO, and vehicle disposal options.

### **Safety and Reliability of NEP**

Safety and reliability of space nuclear propulsion systems are of paramount importance.

Safety encompasses the health and safety of the public, program personnel, mission crew, and the protection of terrestrial and, as appropriate, nonterrestrial environments, and will also include protection of government property against accidental loss or damage, and the safeguarding of special nuclear materials from unauthorized use or diversion. The scope of safety activities will include design, development, fabrication, transportation, ground testing, system integration, launch and deployment, operation, and disposal. Safety will be integrated into the design from conception and will be a key consideration in all design and operational decisions. In FY91, an interagency Nuclear Safety Policy Working Group recommended nuclear safety policy, requirements, and guidelines for the SEI nuclear propulsion program.<sup>5</sup> Starting in FY92, a safety analysis approach will be provided to help guide NEP conceptual design efforts.

High operational reliability for an NEP system for use as primary propulsion for piloted and cargo missions to Mars must be assured. To this end, a task has been initiated to develop an initial plan, methodology, and database required for reliability analysis of an NEP system. Under this study, top level reliability goals will be established for each system element for each mission phase to permit reliability apportionment and redundancy analysis

to be performed and to parametrically investigate redundancy, design issues, and common cause failures. A reliability data collection activity will provide the basis for determining achievable reliability values for NEP systems.

#### CONCEPTUAL DEFINITION OF 100 KWE CLASS NEP

In response to recent direction from NASA HQ to provide a detailed technology development plan and approach to demonstrate technology readiness of the propulsion technologies for a 100 kWe NEP system for use in Office of Space Science and Applications (OSSA) advanced robotic science missions, concept definition activities are being initiated by NASA. To meet OSSA mission requirements, the NEP system would require a space nuclear reactor system having a nominal power of 100 kWe and a specific mass of no greater than 60 kg/kWe. For the OSSA projected need dates, mission requirements can be best achieved by inert gas ion thruster technology.

The scope of the concept definition for 100 kWe NEP is to define potential science missions and requirements, assess applicability of a generic NEP transfer stage, and perform system and vehicle conceptual design. Output from the concept definition study would be system definition at the subsystem/component level, component specific masses, detailed technology design requirements for the electric thrust subsystem, and detailed requirements on the SP-100 space nuclear power system.

#### CONCLUSION

This paper has presented key technical issues associated with megawatt NEP for SEI, and the plans and status in FY92 for their resolution. Also, a concept definition activity is being initiated for 100 kWe NEP for NASA's Office of Space Science and Applications, in response to recent direction from OAST. Issues associated with megawatt NEP are system performance, flight system processing, and the assurance of safety and reliability in the design of NEP systems. A coordinated effort by NASA and DOE to address these issues has been initiated in FY92.

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